Remarks:

Numerous changes have been made to formatting to bring it into line with U.S. filing customs, to change British spellings to U.S. spellings, and to correct several typographic errors. No new matter has been added in making any of the changes.

Applicants believe that the application with Claims 1-28 as amended are patentable at this time. Accordingly, these claims remain pending following entry of this Preliminary Amendment, and the case with Claims 1-28 is believed to be in condition for allowance at this time. Applicants respectfully request entry of this Preliminary Amendment, and an early and favorable consideration of the claimed subject matter as amended is solicited. Should the Examiner believe that the prosecution of the application can be so expedited, the Examiner is requested to call Applicants' undersigned attorney at the number listed below.

Respectfully submitted:

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MARKED-UP VERSION OF THE SPECIFICATION

LASER MULTIPLEXING

BACKGROUND OF THE INVENTION

[0001] Field of the Invention - The invention relates to laser multiplexing for example in high power pulsed lasers.

[0002] One area in which laser multiplexing is required is Extreme Ultraviolet Lithography (EUVL) which is considered to be one of the most attractive candidates to succeed conventional optical lithography in the coming years. This will permit reduction of structure sizes in semiconductor devices to less than 30nm. To enable this technology, a light source is required that emits in the spectral range around 13.5nm. The Laser Produced Plasma (LPP) Extreme Ultraviolet (EUV) source described for example in U.S. Patent Application Publication No. US_2002/0070353_A1, to Richardson, and PCT International Publication No. WO_02/19781_A1, to Taylor et al., has great potential to be the future source for EUV lithography, and offers several advantages over discharge-based EUV sources. These advantages can be ~~summarised~~ summarized as: power scalability through tuning of lasers parameters, low debris, pulse-to-pulse stability (optimum dose control), flexibility in dimensions, spatial stability, minimal heat load, and large solid angle of collection.

[0003] The main requirements for the LPP EUV source are the availability of a refreshable, efficient target as well as high laser repetition rate, high peak intensity, and high average laser power on the

target. In order to generate optimum conversion efficiency (CE) from laser light to EUV radiation (particularly wavelengths in the vicinity of 13.5nm), peak intensity (I) on Xe target is required to be in the range 10^{11}-10^{13} W/cm^2:

$$I(W/cm^2) = E_L/(A\tau) \qquad (1)$$

where E_L is the laser pulse energy (joules), A is the focal spot area of the laser beam on target (cm^2), and τ is the laser pulse duration (seconds).

[0004] Although it is trivial in order to obtain higher powers to combine two highly ~~polarised~~ polarized lasers into one co-linear beam using a ~~polarising~~ polarizing beam splitter and ~~polarisation~~ polarization rotation optics (waveplates), this technique cannot combine more than two lasers and cannot be applied to ~~unpolarised~~ unpolarized lasers.

[0005] In one approach known as Master Oscillator Power Amplifier (MOPA), a single large, complex laser system is employed in order to satisfy the input power requirements. Scale-up is achieved for instance by adding amplifier modules after the laser oscillator in order to boost output power. However various problems arise with this system. Firstly, limited flexibility is offered in terms of scalability. Secondly, if a fault occurs on one of the amplifier modules, the complete EUV system is shut down.

[0006] In another known approach shown in Fig. 1, the outputs of several smaller laser modules 100, 102, 104 are combined using a single focussing optic 106 in order to achieve the required peak intensity (Equation

1) on target 108 and therefore the optimum conversion efficiency. The focal spots of all beams 110, 112, 114 are ideally equal in size and perfectly overlapped in space to ensure that the required peak intensity is achieved.

[0007] However, problems arise with this system as well. For example, the focal spot size of any given beam can depend on its position on the optic's surface if the lens is not of sufficient quality that spherical aberration can be neglected. Furthermore, if the lens diameter needs to be increased, for example to accommodate a larger number of laser beams, it becomes increasingly expensive and difficult to manufacture a lens of sufficient quality. Also, in this system off-axis mirrors are employed in order to arrange the beams on the surface of the focussing optic. However, when using off-axis mirrors, it is difficult to arrange the beams to propagate close together (in order to efficiently use the surface area of the focussing element) because mounting hardware such as lens and mirror holders tend to clip sections of beam path.

[0008] In a further known approach, multiple laser optics are used. This approach to increasing the pulse energy on target using multiple laser beams has been demonstrated extensively in laser fusion work at the Rutherford laboratory, National Ignition Facility (NIF) and other large-scale laser facilities. The method involves focussing many beams from a variety of angles in order to illuminate the fusion target. Each beam-line employs its own focussing element in order

to achieve the desired peak intensity on target. However, in this configuration the beam lines completely surround the target, severely limiting the collection efficiency of any generated EUV radiation.

[0009] A further known approach set out in U.S. Patent Application Publication No. US 2002/0090172 A1, to Okazaki et al., describes a semiconductor diode laser multiplexing system for printing and medical imaging purposes whereby beams emitted from discrete laser diodes converge at the entrance of a multimode optical ~~fibre,~~ fiber, and propagate through the ~~fibre.~~fiber. However, such an arrangement is not suitable for use with LLP EUV laser multiplexing schemes as the high intensity light pulses required (in the range 10^{11} - 10^{13} w/cm^2) would destroy the optical ~~fibre.~~fiber. Moreover, ~~fibre~~ fiber optic delivery severely restricts the solid angle of light collection at the ~~fibre~~ fiber entrance and thereby ~~limiting~~ limits the number of beams that can be multiplexed with such an arrangement.

[0010] The invention is set out in the attached claims.

SUMMARY OF THE INVENTION

[0011] The disadvantages and limitations of the background art discussed above are overcome by the present invention. With this invention, a laser multiplexing system and method for use with high power pulsed lasers in Extreme Ultraviolet Lithography are provided. In a first embodiment, a high power EUV laser multiplexing element for laser produced plasma generation has a compound lens with at least two focusing elements arranged to focus at least two respective laser beams to a focal point on a common workpiece.

[0012] In a second embodiment, a laser multiplexing apparatus has at least two pulsed laser sources for generating pulsed laser beams and a temporal multiplexing element arranged to temporally interleave at least two pulsed laser beams. In a third embodiment, a laser multiplexing assembly has a beam shaping element in which the beam shaping element is arranged to direct a first laser beam along an axis common with a second laser beam axis onto a common focusing element arranged about the common axis.

DESCRIPTION OF THE DRAWINGS

[0013] Embodiments of the invention will now be described, by way of example, with reference to the drawings of which:

[0014] Fig. 1 shows a prior art laser multiplexer;

[0015] Fig. 2 shows a schematic diagram of a spatial laser multiplexer according to the invention;

[0016] Fig. 3a shows a schematic diagram of a temporal laser multiplexer according to the invention;

[0017] Fig. 3b shows a timing diagram for the multiplexer of Fig. 3a;

[0018] Fig. 3c shows an alternative temporal multiplexer according to the invention; and

[0019] Figs 4a, 4b, and 4c show a schematic diagram of a further embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0020] In a first embodiment of the invention shown in Fig. 2, an LPP EUV system is designated generally by reference numeral 200 and includes an LPP chamber 202 of any appropriate type including a collector (not shown) and a target 204. A plurality of laser sources 206a, 206b, and 206c generate laser beams 208a, 208b, and 208c, respectively. The laser beams 208a, 208b, and 208c are directed onto an array of respective closely spaced, small lenses 210a, 210b, and 210c, forming a so-called ~~'fly-eye'~~ "fly-eye" arrangement. Each lens accommodates 1-2 laser beams, and the whole optical assembly constitutes a compound lens that focuses N laser beams onto any type of target or workpiece through a chamber window 205, particularly for the purpose of generating EUV radiation.

[0021] An appropriate laser is a pulsed, diode-pumped solid state laser (e.g. Powerlase model Starlase AO4 Q-switched Nd:YAG laser) providing ~~multi-khz~~ multi-kHz repetition rates and pulses of duration 5-10ns. A standard single element positive lens (plano-convex, or bi-convex, antireflection coated) would be a suitable element for a ~~'fly-eye'~~ fly-eye compound lens (e.g. 300 mm focal length, 1" diameter, fused silica, plano-convex lens with anti-reflection coating for 1064 nm light - CVI Laser LLC, part number PLCX-25.4-154.5-UV-1064). The optical performance could be ~~optimised~~ optimized using any appropriate commercial software package (e.g. Code V from Optical Research Associates).

[0022] Combining multiple lasers using the spatial multiplexing method described above offers several advantages over prior art LPP driver arrangements. For example, compared to using a single high power laser, greater flexibility is offered in terms of scalability. Secondly, if a fault occurs on one of the multiplexed modules, the EUV system can continue to run (albeit at slightly reduced output power).

[0023] Compared to a spatial multiplexing scheme involving a single focussing optic, the focal spot size of any given beam does not depend on its position on the optic's surface such that lens quality is less determinative. However, if the lens diameter needs to be increased, for example to accommodate a larger number of laser beams, in the fly-eye scheme, smaller, readily available and high quality lenses can be employed in order to ~~minimise~~ minimize the effect of aberrations.

[0024] Furthermore, in contrast to systems using multiple independent focussing optics, the fly-eye compound lens gives a larger solid angle in which EUV can be collected as the laser radiation is confined to a narrow cone.

[0025] In a second embodiment shown in Figs. 3a to 3c, the laser power incident on a target is increased using temporal and/or spatial or angular multiplexing to combine several source laser beams into a single, co-propagating output beam of the high repetition rates required for LPP production. The technique may be made independent of the ~~polarisation~~ polarization states of the source laser beams.

[0026] A number of source laser beams 300a, 300b, and 300c of the type described above are directed at an optical element 302, in this case a rotating mirror or prism which introduces a time-varying angular deviation to the beams. The angle of incidence of each source beam 300a, 300b, and 300c upon the deviating element 302 is unique.

[0027] Each source laser beam consists of a train of discrete pulses separated in time by the reciprocal of the laser repetition frequency. As can be seen in Fig. 3b, which ~~illustrated~~ illustrates the system for 3 lasers, the timing of the source lasers is arranged such that their output pulse trains are temporally interleaved, and therefore the arrival time of each laser pulse at the deviating element is unique. The time-variation of the deviating element is arranged such that an incident pulse from any of the source lasers is made to propagate along a common output path.

[0028] In the case of the rotating reflective prism 302 shown in Fig. 3a, the prism is of hexagonal cross-section, although other polygonal cross-sections could be used providing that the number of reflecting surfaces is an integer multiple of the number of laser beams being multiplexed. Because the prism 302 is rotated, and the source laser beams 300a, 300b, and 300c are successively pulsed, a single face of the prism presents a different angle of incidence to each source beam pulse. Accordingly the rate of rotation of the prism can be determined such that the variation in angle of each source beam is effectively

compensated such that the beams are all reflected along a common output path 304. The rate of rotation is also selected such that the reflection angle of a pulse between leading and trailing edges is ~~minimised,~~ minimized, that is, there is no substantial angular spread caused as a result of pulse dwell time, therefore removing the need for compensatory secondary optics.

[0029] It will be appreciated that various alternative arrangements can be provided, for example a reciprocating mirror or the variant shown in Fig. 3c in which a wedge-shaped prism 310 has a source beam input face 312 perpendicular to the direction of the output beam 314 and an output face 316 at an angle to the input face 312. The wedge is rotated such that the output face presents the same angle of incidence to different source laser beams 318a, 318b, 318c, and 318d in turn as ~~these~~ they are sequentially pulsed. Accordingly, the difference in angle of incidence of each of these beams is once again compensated by the rotating wedge to provide a common output path 314. As the laser pulses are equally separated in time and the wedge is rotating at a constant angular velocity, the laser sources are equally separated in angle. Alternatively, the output face may be perpendicular to the direction of the output beam, and the input face may be at an angle to the output face, or both faces may be at an angle to the direction of the output beam.

[0030] The resulting beam is temporally and angularly multiplexed with an average power of N ~~x~~

~~(source~~ multiplied by the source average ~~power)~~ power and a repetition frequency of N ~~x (source~~ multiplied by the source repetition ~~frequency)~~ frequency where N is the number of sources. A beam multiplexed in this way may be further combined (e.g. by use of spatial multiplexing as discussed above).

[0031] As a result of this arrangement ~~polarisation~~ polarization independent multiplexing for multiple lasers can be achieved.

[0032] Furthermore as a result of this arrangement the average power scaling up can be controlled independently from peak intensity on target, i.e. the average power on target can be increased without increasing the peak intensity on the target.

[0033] In a further embodiment, generally designated by reference numeral 400, shown in Figs. 4a and 4b, the system ~~comprises~~ includes beam shaping elements 401 and 402 for forming a beam of annular cross-section, ~~and~~ plane annular mirrors 403 and 404, and a common focusing element 405. The annular mirrors 403 and 404 and the common focusing ~~elements~~ element 405 are arranged about a common longitudinal axis. A plurality of lasers generate laser beams 406a, 406b, and 407. A first and second of the plurality of laser beams ~~406a,~~ 406a and 406b are directed onto respective beam shaping elements ~~401,~~ 401 and 402, respectively, to produce respective annular output beams ~~406c,~~ 406c and 406d (shown in side cross-section). Each of the annular output beams ~~406c,~~ 406c and 406d is directed to a common focusing element 405 using annular mirrors ~~403,~~ 403 and 404,

respectively, (shown in side-cross-section) angled to the beam direction such that the directed beam propagates along a common axis. An additional laser beam 407 is directed to the common focusing element by a plane mirror 420. The annular mirrors 403 and 404 and the plane mirror 420 are orientated substantially parallel to each other, and are arranged to form a concentric beam pattern at the common focusing element 405. The common focussing element 405 is shown in end view in Fig. 4b ~~on~~ in which figure the spatially separated annular beams can be seen to be incident concentrically.

[0034] Preferably, each beam shaping element is formed of a pair of conical or "axicon" lenses of the type described at www.sciner.com/Opticsland/axicon.htm and as shown in Fig. 4c. In this arrangement, the circular input beam is divided by a first axicon lens 408 to produce a divergent annular shaped beam which is incident on a second axicon lens 410, to produce a substantially collimated annular output beam. Alternatively, diffractive optics such as diffraction gratings could be employed to produce the annular shaped beams.

[0035] Three beams have been shown in Fig. 4a, but in principle any number of beams could be multiplexed in this way, the maximum number of beams being ultimately limited by the aperture of the focussing element.

[0036] Combining multiple lasers using beam shaping techniques of the type described above offers several advantages over prior art arrangements. For example,

by using annular beams which propagate along a common axis, the need for off-axis mirrors and the alignment problems associated therewith are removed.

[0037] It will be appreciated that the temporal or spatial multiplexing schemes can be coupled in any appropriate manner whereby temporally interleaved or overlapping beams can be incident on a common "channel" spatially multiplexed with other such beams.

[0038] The combination of spatial and temporal multiplexing allows the laser average power on the EUV target to be scaled up, as a result increasing the EUV average power output. This is achieved as follows from equation 1: laser power intensity on target is increased until optimum conversion efficiency of EUV radiation is achieved, then scaling up the average power is achieved by temporal multiplexing.

[0039] It will be appreciated that individual elements and steps from the various embodiments can be combined or juxtaposed as appropriate. Any appropriate laser can be used, together with any appropriate optical elements such as reflective, refractive, or diffractive deviation elements to achieve the desired effects. Also, the approach can be used to obtain high powers for any appropriate application and continuous lasers can be used where appropriate. The approaches, when combined, can be combined in any order.

[0040] Although the foregoing description of the present invention has been shown and described with reference to particular embodiments and applications thereof, it has been presented for purposes of

illustration and description and is not intended to be exhaustive or to limit the invention to the particular embodiments and applications disclosed. It will be apparent to those having ordinary skill in the art that a number of changes, modifications, variations, or alterations to the invention as described herein may be made, none of which depart from the spirit or scope of the present invention. The particular embodiments and applications were chosen and described to provide the best illustration of the principles of the invention and its practical application to thereby enable one of ordinary skill in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. All such changes, modifications, variations, and alterations should therefore be seen as being within the scope of the present invention as determined by the appended claims when interpreted in accordance with the breadth to which they are fairly, legally, and equitably entitled.

MARKED-UP VERSION OF THE ABSTRACT

LASER MULTIPLEXING

ABSTRACT OF THE DISCLOSURE

A laser multiplexing system and method for use with high power pulsed lasers in Extreme Ultraviolet Lithography is disclosed. In a first embodiment, a high power EUV laser multiplexing element ~~(200)~~ for laser produced plasma generation ~~comprises~~ has a compound lens ~~comprising~~ with at least two focusing elements ~~(210)~~ arranged to focus at least two respective laser beams ~~(208)~~ to a focal point ~~(204)~~ on a common workpiece. In a second embodiment, a laser multiplexing apparatus ~~comprises~~ has at least two pulsed laser sources for generating pulsed laser beams and a temporal multiplexing element ~~(302)~~ arranged to temporally interleave at least two pulsed laser beams ~~(300)~~. In a third embodiment, a laser multiplexing assembly comprises a beam shaping element ~~(401)~~ in which the beam shaping element is arranged to direct a first laser beam ~~(406a)~~ along an axis common with a second laser beam ~~(406b)~~ axis onto a common focusing element ~~(405) arranges~~ arranged about ~~said~~ the common axis.